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(54) **Resolution doubling lithography technique.**

(57) A lithography system is disclosed which is capable of doubling the spatial frequency resolution associated with conventional systems. A spatial filter (e.g., 20), positioned to intercept the Fraunhofer diffraction pattern of the mask (e.g., 18) being exposed, is configured to prevent certain orders of the diffraction pattern (in most cases the 0-order and ±2nd, 3rd, ... orders) from reaching the wafer's surface. The remaining orders reaching the wafer surface (in most cases the ± first-order beams) will produce a cos-type interference pattern with a period half of that if the mask grating were imaged without spatial filtering. Therefore, for a system with a given magnification factor m, a mask grating with a period p will be exposed on the wafer surface as a grating with a period of $p' = pm/2$. Advantageously, the spatial filtering technique of the present invention allows for a variety of different structures (conventional gratings, chirped and phase-shifted gratings, grids, Fresnel zones plates, etc.), as well as structures of different sizes and orientations, to be included on one mask and transferred to the wafer with a single exposure cycle.

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filtering in the Fourier transform plan of the mask to provide twice the resolution of conventional lithographic systems.

In accordance with the present invention, an aperture filter is located at the position within the system where the Fourier transform (Fraunhofer diffraction pattern) of the mask will appear (within the projection lens system positioned above the wafer). In one embodiment, the filter is configured to block the zero-order (undiffracted) radiation diffracted by the mask into the lens system. The blocking of the zero-order beam has been found to result in the frequency doubling of the magnified mask grating, by virtue of the interferenc of the remaining ±first-orders of diffraction on the wafer surface (the filter is configured to also block the higher order beams - ±2nd, 3rd, etc.). This technique thus combines an interference of two beams (±first-order) with the conventional imaging technique as found in prior art projection lithography. In fact, the insertion of such a spatial filter into a standard photolithography system requires only a sight modification, yet results in doubling the resolution of the system. Thus, various photolithographic exposure systems (e.g., Cassagrain-type reflective systems, double-Gauss lens design refractive systems) may utilize this spatial blocking technique.

In another embodiment of the present invention, spatial filtering in the mask Fourier transform plane may be utilized in lithographic systems having oblique illumination, i.e., where the illumination source is off-axis and the spatial filter allows only the 0-order and one first-order beam to interfere. When used with a coherent (or partially coherent source), this filtering and interference technique provides twice the resolution of other coherent systems (with a contrast approaching 100%).

An advantage of the present technique of blocking of the zero-order beam is that it has been found to provide a much higher contrast (≈ 100%) and a much larger depth of focus (±13 μm) than other deep-UV photolithographic systems (typical values: contrast 50%-60%; depth of focus ≈ ±1μm). As a result of either using a small illumination source, or small holes in the filter, this system is also less sensitive to lens aberrations than conventional projection lithographic systems.

Another advantage of the spatial filtering technique of the present invention is that gratings with different periods, or gratings with chirp in their period, may be formed at any location on the wafer with only a single exposure. In particular, gratings with different periods, sizes, configurations and orientations can all be produced on the same chip with a single exposure. In fact, this system may be used to print a variety of structures including grids, circles and zone plates. Thus, the present spatial filtering technique finds wide application for the formation of a variety of structures.

Yet another advantage of the present technique is that it is not wavelength-dependent and thus is compatible with virtually any type of illumination source - x-ray, visible, UV, near-UV, deep-UV, etc.

Other and further advantages of the spatial filtering technique will become apparent during the course of the following discussion and by reference to the accompanying drawings.

Brief Description of the Drawing

FIG. 1 illustrates, in a diagram form, an exemplary lithographic system of the present invention;

FIG. 2 illustrates an exemplary mask, including a variety of grating structures, grids, circles and zone plates which may all be exposed with the spatial filtering system of the present invention;

FIGs. 3-5 illustrate various spatial filters which may be included in the system of FIG. 1;

FIG. 6 represents the spatial function describing one exemplary grating structure of FIG. 2;

FIG. 7 represents the spectrum of the geometrical image of the spatial function of FIG. 6, with an exemplary spatial filter formed in accordance with the present invention also illustrated in FIG. 7;

FIG. 8 represents the amplitude distribution of the electric field, in the image plane, of the exemplary grating structure;

FIG. 9 represents the final image irradiance of the frequency-doubled grating structure which impinges the surface of the resist on the wafer;

FIG. 10 illustrates an alternative, obliquely illuminated, lithography system, utilizing the spatial filtering technique of the present invention; and

FIG. 11 is representative of the spectrum of the geometrical image obtained from the oblique illumination system of FIG. 10; and

FIG. 12 is an SEM photograph of an exemplary grating with a period of 0.5 μm (0.25 μm feature size) formed using the spatial blocking technique of the present invention.

Detailed Description

as indicated in the drawing. With the blocking of the 0-order beam by filter 22, the illumination reaching the surfac of wafer 20 will not be an image of the mask grating, but in reality the cosine-type interference fringes produced by the interfering first-order beams which are allowed to pass through apertures 24,26 of filter 22. The result of this interference is that the period of the filtered illumination will be twice as small as the period of the grating would be if imaged through a conventional lensing system. Therefore, a mask grating with a period of 5.0 μm will produce a grating with period 0.5 μm on the wafer surface. The resolution of the inventive projection system is thus doubled, when compared with conventional systems, by blocking the 0-order beam from the wafer surface.

FIG. 4 illustrates an alternative blocking filter 28 which includes a vertical stripe 30 for blocking the 0-order beam. Another filter design which also allows the higher orders to be passed is illustrated in FIG. 5. As shown, filter 32 of FIG. 5 includes a central obstruction 34 which is designed to block only the 0-order beam. This filter will allow to pass two first orders diffracted by object gratings oriented in any direction on the mask (45°, vertical, horizontal, etc.). The arrangements of FIGs. 4 and 5 are considered to be less sensitive to system misalignment than the arrangement of FIG. 3, since the diffraction pattern may be significantly offset from the masks in either the horizontal or vertical directions, and the first-order beams will still pass through and interfere at the wafer's surface. In contrast, a slight misalignment of filter 22 (as shown in phantom in FIG. 3) will result in a portion of at least one of the first-order beams being blocked. It is to be understood, however, that the arrangement of FIG. 3 has the advantage of reducing the amount of stray (background) light reaching the wafer surface, thus providing a higher contrast image when compared to the filter designs of FIGs. 4 and 5. In addition, it may filter out many mask imperfections, such as scratches and dust particles.

The following description will provide a detailed analysis of the exposure of the exemplary grating structure A depicted in FIG. 2. This particular grating structure was chosen merely to simplify the mathematics which are presented below. It is to be understood that the 0-order blocking technique may be used to expose virtually any grating pattern.

A typical grating pattern A can be described by the relation:

$$t(x,y)=\left[\mathrm{rect}\left(\frac{2x}{p}\right)*\left(\frac{1}{p}\right)\mathrm{comb}\left(\frac{x}{p}\right)\right]\mathrm{rect}\left(\frac{x}{a},\frac{y}{b}\right), \qquad (1)$$

where p is the period of the grating, a and b the grating dimensions in the x and y directions, respectively (p, a and b are illustrated in FIG. 2),

$$\mathrm{rect}\left(\frac{2x}{p}\right)$$

is a zero-one function of width p/2,

$$\mathrm{comb}(x)=\sum_{n=-\infty}^{\infty}\delta(x-n),$$

δ(x) is Dirac δ function and * denotes a convolution operation. FIG. 6 illustrates this particular function. The Fraunhofer diffraction pattern (spectrum) of an illuminated object is its Fourier transform. Thus, in accordance with the present invention, the spatial filtering is performed at the aperture plane of the lens system, which is placed in the frequency plane of the object, i.e. the plane where Fraunhofer diffraction pattern of the object is displaced. For grating pattern A, the Fourier transform is given by the following:

$$T(\xi,\eta)=\left[\frac{p}{2}\,\mathrm{sinc}\left(\frac{p}{2}\xi\right)\mathrm{comb}\left(p\xi\right)\delta(\eta)\right]**(ab)\mathrm{sinc}(a\xi,b\eta), \qquad (2)$$

where ξ and η are the spatial frequencies of the grating in the x and y directions, respectively, and

$$\Delta x = \frac{2\lambda z}{m_p}\Delta\xi,$$

placed at a distanc

$$x_o = \frac{\lambda z}{m_p}\xi_o$$

.

from the center of the filter.

The spectrum of the diffracted image after it passes through the filter may thus be obtained by multiplying equations (3) and (4) together:

$$\begin{aligned}U(\xi,\eta) &= T'(\xi,\eta)\,H(\xi,\eta)\\ &= \frac{1}{m\pi}\left[\delta\left(\xi+\frac{1}{m_p}\right)+\delta\left(\xi-\frac{1}{m_p}\right)\right] * (m^2ab)\,\mathrm{sinc}\,(ma\xi, mb\eta), \qquad (5)\end{aligned}$$

where

$$\mathrm{sinc}\left[\frac{1}{2}\right]=\frac{2}{\pi}$$

has been used. The complex amplitude of the image may then be obtained by performing an inverse Fourier transform on equation (5):

$$u(x,y)=\left(\frac{2}{m\pi}\right)\cos\left(\frac{2\pi x}{mp}\right)\mathrm{rect}\left(\frac{x}{ma},\frac{y}{mb}\right), \qquad (6)$$

the approximation related to the assumption that the sinc-function components of the spectrum are so narrow, relative to the width of filter $H(\xi,\eta)$, that they will either be passed or completely eliminated. Since the 0-order term (as well as higher orders: 2nd, 3rd, etc.) has been blocked by filter 22, the image amplitude varies as a cosine function with a period p' equal to the period p of the grating multiplied by the magnification factor m of the system.

Lastly, the irradiance at the image plane is given by:

$$\begin{aligned}I &= |\,Au(x,y)\,|^2\\ &= \left(\frac{2A}{m\pi}\right)^2\cos^2\left(\frac{2\pi x}{mp}\right)\mathrm{rect}\left(\frac{x}{ma},\frac{y}{mb}\right)\\ &= 2\left[\frac{A}{m\pi}\right]^2\left(1+\cos\frac{2\pi x}{mp/2}\right)\mathrm{rect}\left(\frac{x}{ma},\frac{y}{mb}\right), \qquad (7)\end{aligned}$$

where A is the coefficient which depends on the magnitude of the illuminating wave field and the losses in the optical system. The image irradiance is illustrated in FIG. 9. Since the irradiance is a squared function of the amplitude, it will also be a cosine function, with a period half that of the amplitude distribution. That is, if the desired grating period in the image is p', the period on the mask grating should be $p = 2p'/m$.

be somewhat distorted. The disadvantages are that only high frequency gratings approximately in the direction of the oblique illumination may be printed, and it may be difficult to provide such oblique illumination in a conventional camera system.

In summary, the on-axis frequency doubling spatial filtering technique would be utilized in situations where there are gratings oriented in several directions, or where the mask contains only grating structures. Oblique illumination may be preferred alternative when it is desirable to print coarse features as well as gratings, as long as the gratings are all oriented in approximately the same direction.

If the mask contains gratings of the same period, but with duty cycles other than one-half (i.e., unequal size of lines and spaces), their images will look exactly the same as the images of gratings with equal lines and spaces. The difference in duty cycle will only affect the width of the envelope sinc functions in the image spectrum, which results in change of the percentage of the light diffracted into two first orders.

It is possible to produce the grating with duty cycles different than one-half by overexposing or underexposing the resist film which will result in different line width in the grating after the development and etching process.

EXAMPLE

Gratings with a period of 0.5 µm were fabricated using the spatial frequency doubling system of the present invention. The system used a KrF excimer laser, operating at 248.4 nm as its illumination source. A 5X reduction (0.2 magnification factor) fused silica lens with a numerical aperture of 0.38 and a 14.5 mm diameter field was used as the projection system. The mask contained 2.5 mm x 1.25 mm gratings of 5 µm period uniformly distributed across the mask's field. The spatial filtering was accomplished by placing a filter with two openings (6.2 mm x 3.1 mm, spaced 30.1 mm apart) into the projection lens.

The wafers to be exposed included a 10 µm thick oxide top surface layer upon which a conventional deep UV-tri-level photoresist was deposited. FIG. 12 is an SEM photograph of the pattern transferred into the photoresist. As shown, well-defined gratings with a period of 0.5 µm were formed. The wafer period of 0.5 µm being a result of the mask period multiplied by the magnification factor, then divided by 2, the division the result of the frequency doubling technique of the present invention.

In accordance with the teachings of the present invention, therefore, it is possible to double the resolution of a standard projection system by inserting a 0-order blocking filter at the position within the projection system where the Fraunhofer diffraction pattern (Fourier transform) of the mask appears.

Claims

1. A lithography system (e.g., 10) for exposing patterns consisting of regular lines and spaces on a wafer surface, the system comprising
an illumination source (e.g., 12);
a mask (e.g., 18) containing at least one pattern with a predetermined period p which is illuminated by said illumination source, a Fraunhofer diffraction pattern, including a 0-order, ± first order and a plurality of higher-order beams, created by the illumination passing through the at least one pattern; and
an imaging system (e.g., 14, 15, 16) with a predetermined magnification factor m disposed between the mask and the wafer for directing the illumination towards the wafer surface,
CHARACTERIZED IN THAT
the imaging system includes a spatial filter (e.g., 22) positioned to intercept the Fraunhofer diffraction pattern, said spatial filter including a central obscuration.

2. A lithography system as defined in claim 1 wherein the illumination source is chosen from the group consisting of coherent illumination and partially coherent illumination, such that the central obscuration of the spatial filter completely intercepts the 0-order beam of the Fraunhofer diffraction pattern, wherein the at least one pattern exposed on the wafer surface comprises a period $p' = pm/2$.

3. A lithography system as defined in claim 2 wherein the illumination is coherent.

4. A lithography system as defined in claim 3 wherein the illumination source is chosen from the group consisting of excimer laser sources, x-ray sources, visible sources, UV sources, near-UV sources, and deep-UV sources.

5. A lithography system as defined in claim 2 wherein the illumination source is partially coherent.

6. A lithography system as defined in claim 2 where the at least one pattern contained in the mask is

FIG. 12

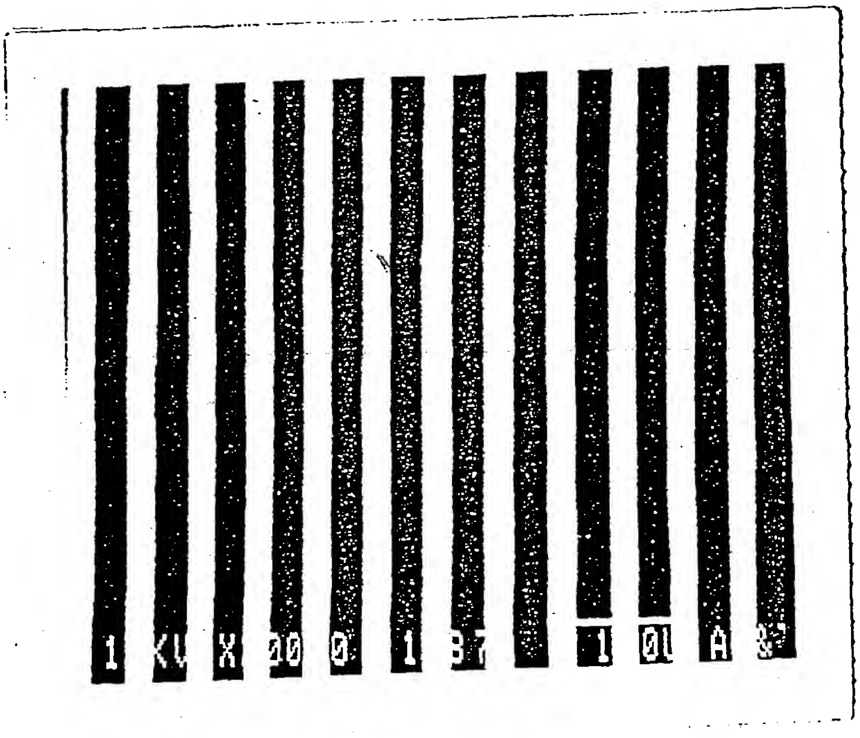

FIG. 10

30

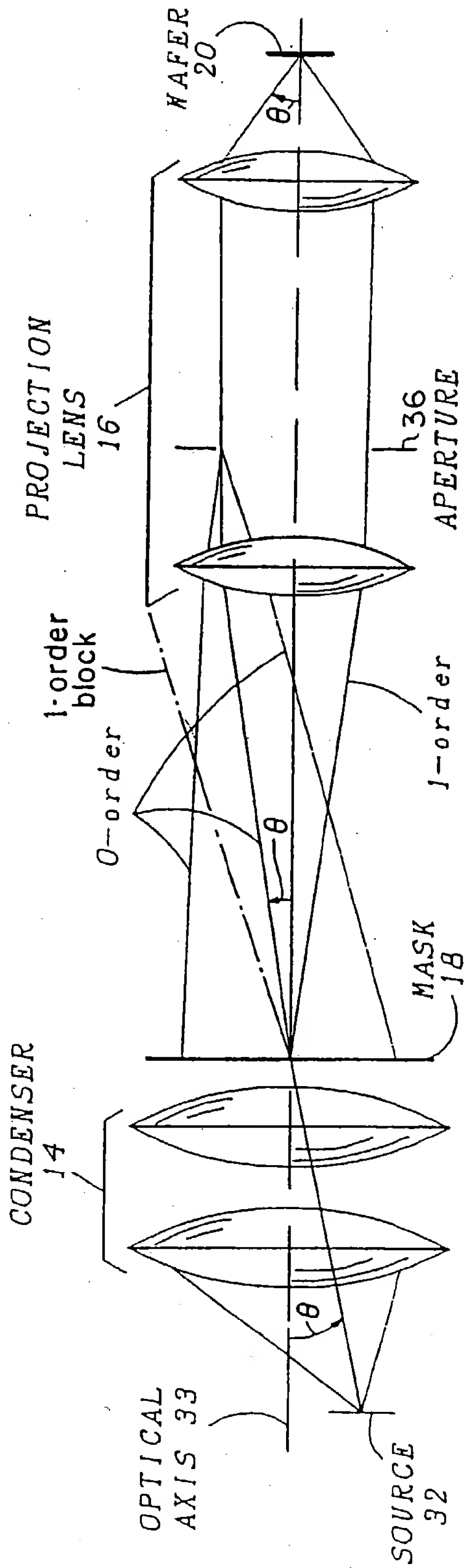
WAFER
20
θ1
PROJECTION
LENS
16
36
APERTURE
1·order
block
0—order
θ
1—order
MASK
18
CONDENSER
14
θ
OPTICAL
AXIS 33
SOURCE
32

FIG.6

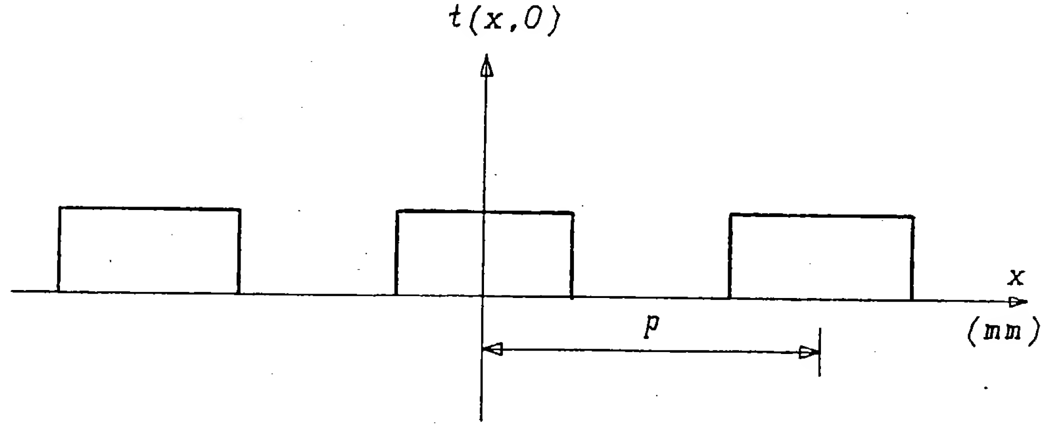
t(x,0)
x
(mm)
p

FIG.7

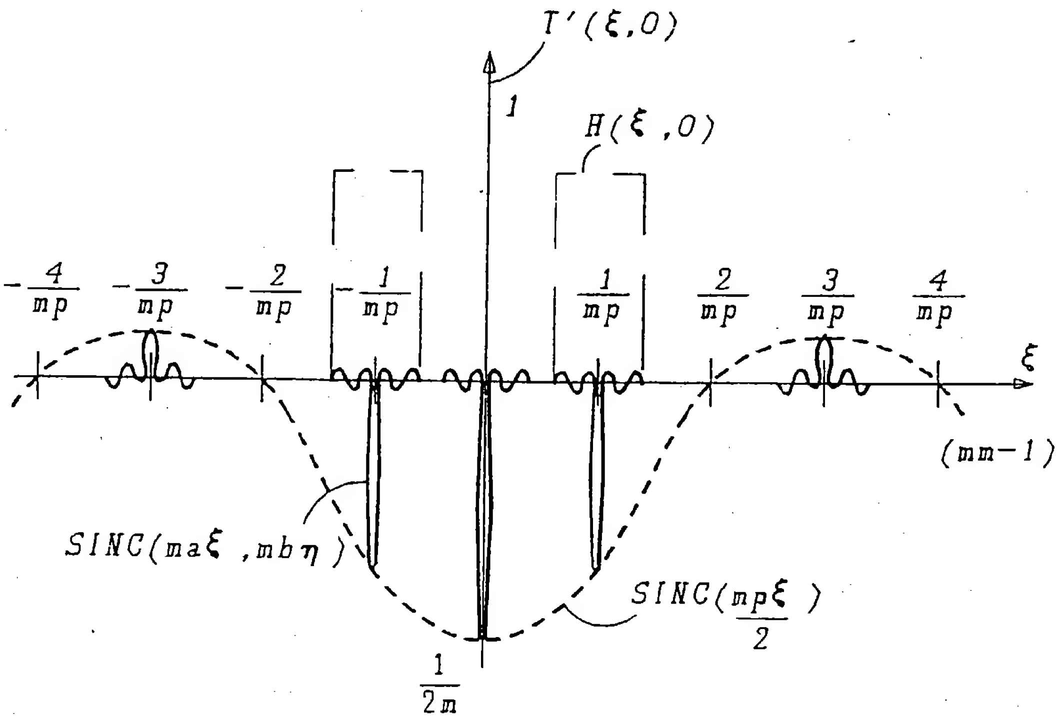
T'(ξ,0)
1
H(ξ,0)
-4/mp
-3/mp
-2/mp
-1/mp
1/mp
2/mp
3/mp
4/mp
ξ
(mm-1)
SINC(maξ,mbη)
SINC(mpξ/2)
1/2m

FIG.2

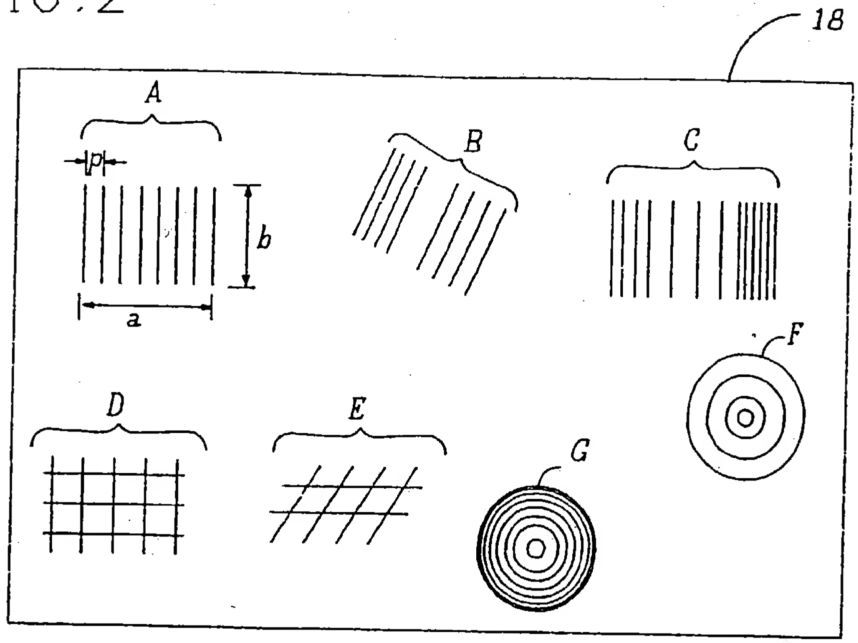

FIG.3